MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

22nd Annual International Symposium
October 22-24, 2019 | College Station, Texas

External Fire Impacts on the Interior Temperature of a Building

Benjamin R. Ishii* and Cristian Jimenez
Quest Consultants Inc. ®
Norman, Oklahoma
*Presenter E-mail: bri@questconsult.com

Abstract

Facility siting studies are an important part of process safety, and are required for facilities that fall under OSHA's PSM program. Facility siting is frequently interpreted as performing a building siting study which adheres to the guidance given in API RP 752. The guidance recommends that all occupied buildings be evaluated for fire impacts. Both jet fires and pool fires can create a significant thermal radiative flux on buildings and are routinely evaluated in siting studies. Buildings that may be impacted by thermal fluxes exceeding threshold values often require an advanced analysis, especially when a non-flammable building may experience a high flux for a short duration. For these scenarios, the interior temperature rise, rather than structural impacts, may be the dominant occupant threat. This paper explores the impacts of an external fire on the interior temperature of a building. The Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) code, is applied to this scenario.

Keywords: CFD, jet fire, pool fire, thermal hazard, building siting

1 INTRODUCTION

Protection of plant personnel for facility siting purposes is typically addressed through the application of the American Petroleum Institute (API) recommended practice (RP) 752[1], which is primarily focused on the location and vulnerability of occupied buildings. These buildings, where personnel carry out their duties, are assumed (within the context of API RP 752) to provide some protection from accidents that may occur at the facility. However, the potential effects on personnel in buildings are highly dependent on the way the equipment and processes are laid out within the facility, the type of building construction, and the distribution of buildings within the plant boundaries, specifically their proximity to hazardous chemicals at the plant.

An analysis conducted to satisfy API RP 752 generally should include three classes of hazards:

- Explosion overpressure or blast wave exposure
- Fire radiation exposure, including pool fires, jet fires, and exposure to an ignited flammable vapor cloud (flash fire)
- Toxic gas exposure

The focus of this work addresses internal temperature rise in buildings due to exposure from fire radiation.

2 FIRE RADIATION IMPACTS

Occupied buildings can be impacted by many forms of fire radiation including:

- Fireballs due to instantaneous releases of flammable fluids, including boiling liquid expanding vapor explosions (BLEVEs)
- Vapor cloud fires (flash fires) due to a release that forms a flammable vapor cloud
- Jet (torch) fires due to continuous, pressurized releases of flammable fluids
- Pool fires due to pooled releases of flammable liquids

The vulnerability of building occupants to fire radiation is certainly mitigated by the building being a physical barrier to the direct effects of fire radiation. However, there are several concerns for the building itself that affect occupant vulnerability:

- Building materials that are combustible could be ignited if the radiative flux and exposure duration are sufficient;
- The integrity of non-combustible materials can be compromised due to degradation or deformation following exposure to radiative heat flux for a sufficient exposure time, resulting in building collapse; or,
- The increased temperature of the building shell exposed to thermal radiation results in a significantly increased interior temperature.

In cases where the building is exposed to thermal radiation and the building does not ignite, there is a possibility for the interior air temperature to increase such that the environment is inhospitable to building occupants. The internal air temperature is a function of the building properties, exposure time, and the intensity of the incident thermal radiation. The vulnerability of building occupants depends on the elevated temperature, the exposure duration, and humidity.

In all cases of exposure to thermal radiation, the magnitude of the radiative flux and the duration of exposure are equally important variables. The principle behind this, whether the exposure is burns to a person’s skin, ignition of wood, or weakening of structural steel, is the temperature rise that occurs. For building interior temperatures, the principles are the same; the flux, magnitude, and exposure duration affect the building shell such that the interior temperature rises.

3 BUILDING SITING

The methodology and tools available for safety siting studies are generally well known within the process safety community. The methodology can be structured as a staged process that allows the study to stop at multiple points when the analysis shows that the impacts, or risk, to the subject population (building occupants) is found to be tolerable. These methodologies have been summarized in several published papers[2] [3].

The specifics of radiative loading on buildings has been addressed by various international agencies[4] [5] [6]. In these publications, the vulnerability of building occupants was estimated using a fixed value of thermal radiation (e.g., 35 kW/m^2) without any mention of the duration of exposure.

Recent studies have shown that building structures may be able to withstand higher levels of thermal radiation (above 35 kW/m^2) without losing structural integrity[7][8]. However, higher radiation values and/or longer durations may impact the temperature in buildings such that occupants are put in danger from hyperthermia or hyperpyrexia. The cutoff between the hyperthermia and hyperpyrexia is distinguished by a core temperature of 41 ºC[9]. Humans can withstand higher temperatures for short durations. For example, many people enjoy 5 minute stays in saunas, which are kept at approximately 80 ºC. The physiological impact is better described as a function of air temperature, humidity, and duration. But for the purposes of this paper, the simple threshold of 41 ºC is sufficient.

In addition previous work has been performed to show that CFD models can predict temperature rise in buildings due to external heat loads. Chakrabarty et al. utilized CFD models to compare temperature rise in a blast resistant module to a concrete masonry building, where both buildings were exposed to external thermal radiation[10]. Raibagkar and Edel modeled internal building temperatures due to thermal radiation exposure to the sides and top of a building[11].

4 CFD Software

The fire dynamics simulator (FDS) is a computational fluid dynamic CFD software developed by the National Institute of Standards and Technology (NIST). FDS began as a finite difference model of fire driven fluid flows. The software also computes thermal radiation transport equations using a finite volume technique. A full description of the model is given in the FDS Technical Reference Guide[12].

In FDS heat is transferred through convection, conduction, and radiation. FDS employs a 3-dimensional mesh to simulate convection, fluid flow, etc., but in some cases a one dimensional simulation can increase the speed of the calculation, as is the case for conduction through solids. By default FDS simplifies heat conduction through solids by simulating one dimensional heat conduction. FDS solves the following equation:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + q$$

Where

ρ = Density

c_p = Heat capacity

k = Conductivity

q = Rate of energy from chemical reactions and radiative absorption

5 Numerical Modeling

Two buildings were modelled with FDS. The first building was modelled as a concrete building with metal doors, similar to the building modelled by Raibagkar. The second building was modelled with the same metal doors, but the walls and ceiling are constructed with a skin of metal, insulation, and gypsum board. The physical properties of the materials used in the modeling are presented in Table 1. For the concrete building, the ceiling consisted of 50.8 mm (2 in) concrete and the concrete walls consisted of 152 mm (6 in) of concrete. All doors in this study were modelled as one inch of insulation sandwiched between two layers of 18 gauge steel. For the insulated metal building, the walls and ceilings of the metal building consisted of 24 gauge steel, 88.9 mm (3.5 in) of insulation, and 12.7 mm (0.5 in) of drywall or gypsum board.

Both buildings are 13 m by 7 m and 4.5 m tall. Each building has two doors located on the opposite long sides of the building. The building is illustrated in Figure 1.

Table 1. Properties of Building Materials

Material	Specific Heat [kJ/kg K]	Conductivity [W/m K]	Density [kg/m3]
Concrete	1.04	1.8	2280
Steel	0.46	45.8	7850
Insulation	1.7	0.05	28
Gypsum Board	0.95	0.19	700

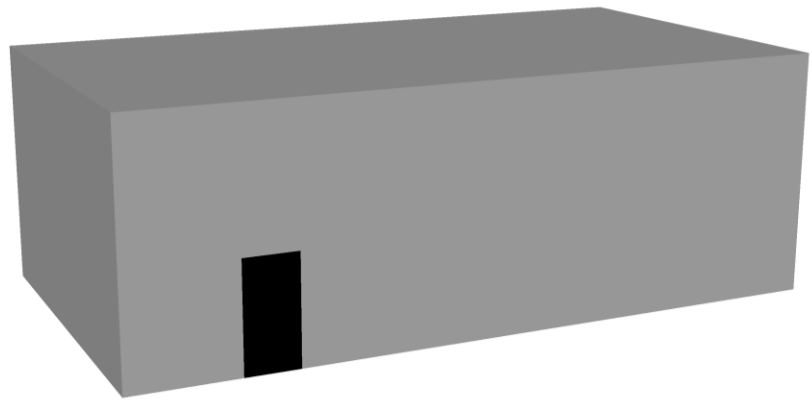

Figure 1. 3-Dimensional View of Building

In the study performed by Raibagkar all sides and the top of the building were exposed to thermal loads. In most fire scenarios, only one to three faces of a building are exposed to thermal radiation at one time. One face of the building exposed to a constant and even level of thermal radiation was applied to this study to simulate a more realistic single fire scenario. Both buildings were exposed to thermal radiation on one 13m by 4.5 m wall. The metal building was exposed to 35 kW/m^2 for one hour. The concrete building was modelled with the following thermal radiant levels for one hour.

- 35 kW/m^2
- 50 kW/m^2
- 75 kW/m^2
- 100 kW/m^2

The model did not account for smoke generation, smoke infiltration, or fire impingement. The scope of this paper is focused solely on occupant vulnerability due to the interior temperature of the modeled buildings.

6 RESULTS

Figure 2 shows the rise of the internal air temperature due to thermal flux on a single face of a concrete building. The temperature is measured in the center of the building at a height of 1.8 meters. All four curves show that there is about a 350 second delay in the temperature rise. The results show that the internal temperature exceeds 41 ºC for exposure to 50 to 100 kW/m^2 at the end of one hour.

Figure 3 presents the temperature history at the center of the building at 1.8 m height, the interior face of the wall, and the interior face of the door for a concrete building exposed to 35 kW/m^2. The data shows that the heat transfer is dominated by the metal door in the first 20 minutes and then the wall drives the rise in temperature.

The results of an insulated building with metal siding with one face exposed to 35 kW/m^2 is presented in Figure 4. Again the results show a similar 350 second delay in temperature rise in air temperature as also shown in Figure 2. The results show that the temperature rises to 45 ºC after one hour. The heat transfer is dominated by the door for the first 10 minutes and the interior wall temperature exceeds the interior door temperature between 15 and 20 minutes after the scenario begins.

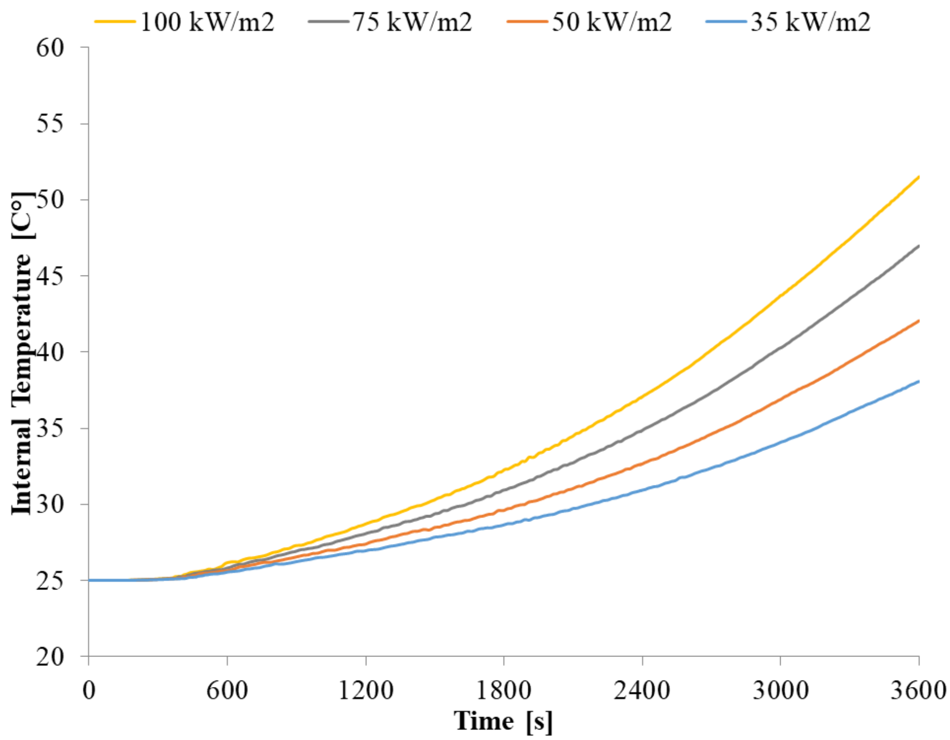

Figure 2
Internal Temperature of a Concrete Building with One Side Exposed to Thermal Radiation

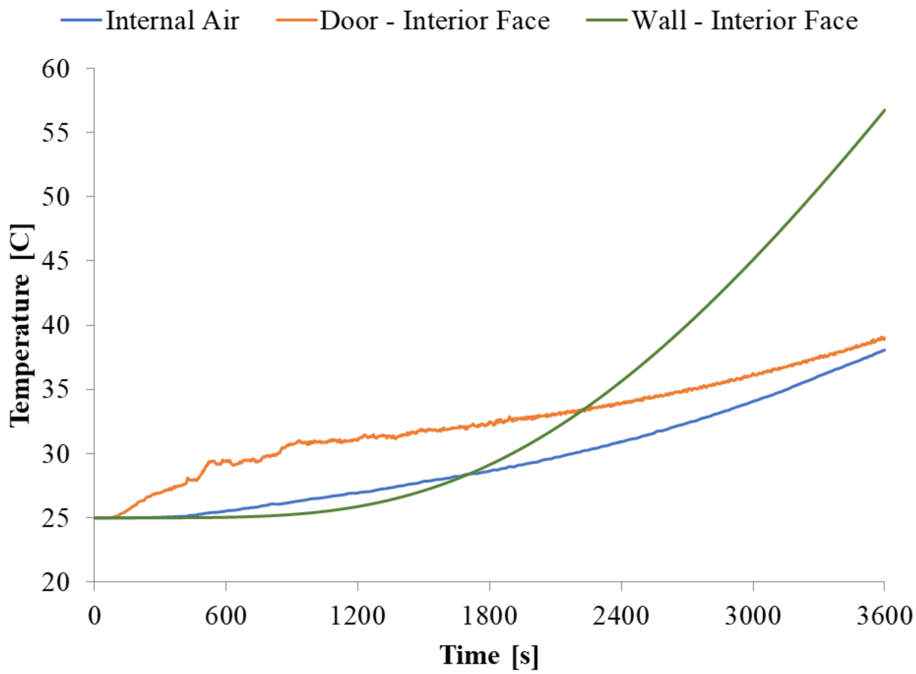

Figure 3
Temperatures in a Concrete Building with One Side Exposed to 35 kW/m^2

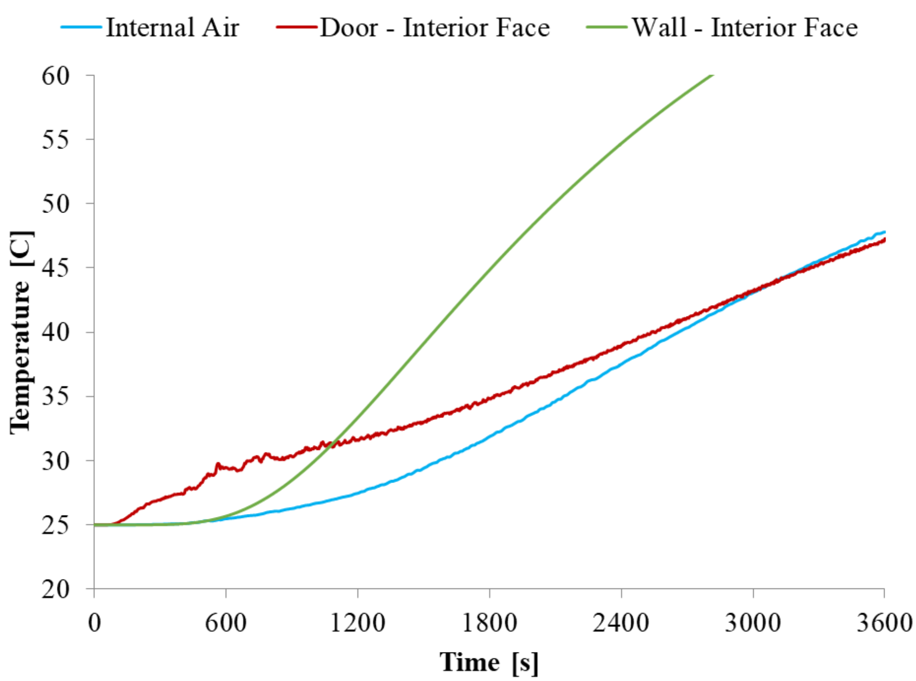

Figure 4
Temperatures in a Metal Building with One Side Exposed to 35 kW/m^2

7 Conclusion

Based on the analysis results provided above, the following conclusions and observations are drawn:

- CFD tools, such as FDS, can successfully model the temperature rise in a building due to exposure to thermal radiation from a fire.
- Buildings with non-flammable exteriors may offer occupants shielding from high levels of fire radiation (greater than 35 kW/m^2) especially for short durations.
- The protection that building may provide occupants depends on the building materials.
- Building siting and shelter in place designation should consider the duration and intensity of potential fires.

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